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DEPARTMENT OF ENGINEERING MECHANICS

Notre Dame, Indiana

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Progress Report No. 15

Dear Sir:

This progress report covers two phases of investigation: the first phase on the evaluation of forces and moment experienced by the trailing ship is nearing completion and these forces and moment are included in this progress report; the second phase of the work in hydrofoils is in a preliminary state, and it is concerned with the method of solution to this problem together with a review of the previous published Russian reports on this subject.

Very sincerely,

Adolf G. Strandhagen

Adolf G. Strandhagen
Director of Project

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Part I Wave Forces

In February, 1954, we forwarded a frief letter to Mr. Bryson, ONR/Chicago, concerning the highlights on the numerical evaluation of some of the significant force and moment components experienced by a ship which is moving directly behind and in the path of a leading ship. At that time a few isolated points were calculated and they revealed details which were significant. The graphs for the force and moment components representing additional wave forces and moment caused by the leading ship were of oscillatory nature. This study suggested that by judiciously spacing the two ships, an appreciable reduction in forces and moment could be obtained. However, the curves did not show any regular trend at that time. Since then, upon closer investigation, and by using smaller intervals for the calculations, a definite trend has been established. In addition, further work has been completed on other force and moment components.

As far as the effect of waves is concerned, the force and moment experienced by the trailing ship may be classed into three parts: the force and moment of ships alone; the force and moment due to mutual interaction between the two ships; and the force and moment due to wave interference. The force and moment components which are due to mutual interaction vary inversely as the square of the distance between the two ships. Hence, for any practical distance between the ships, these components are no doubt very small and will be neglected in the calculations. Concerning the first and third parts listed above, for a given set of parameters, the numerical calculations have been completed for the following force and moment components.

$$X_5'' = -\frac{32\rho K_0^2 b^2 c^2}{\pi l^4}\int_0^d\int_{-l}^{l} h'dh'df' \int_0^d\int_{L-l}^{L+l}(h-L)\,dh\,df$$

$$\times\int_0^{\frac{\pi}{2}}\sec^3\theta\left\{\cos\left[K_0(h'-h)\sec\theta\right]\right\}e^{-K_0(f+f')\sec^2\theta}\,d\theta$$

$$Z_4'' = -\frac{32\rho K_0^2 b^2 c^2}{\pi l^4}\int_0^d\int_{-l}^{l} h'dh'df' \int_0^d\int_{-l}^{l} h\,dh\,df$$

$$\times\int_0^{\frac{\pi}{2}}\sec^4\theta\left\{\sin\left[K_0(h'-h)\sec\theta\right]\right\}e^{-K_0(f+f')\sec^2\theta}\,d\theta$$

$$Z_5'' = -\frac{32\rho K_0^2 b^2 c^2}{\pi l^4}\int_0^d\int_{-l}^{l} h'dh'df' \int_0^d\int_{L-l}^{L+l}(h-L)\,dh\,df$$

$$\times\int_0^{\frac{\pi}{2}}\sec^4\theta\left\{\sin\left[K_0(h'-h)\sec\theta\right]\right\}e^{-K_0(f+f')\sec^2\theta}\,d\theta$$

$$M_5' = -\frac{16\rho K_0^2 b^2 c^2}{\pi l^4}\int_0^d\int_{-l}^{l}(f'-e)\,h'dh'df' \int_0^d\int_{-l}^{l} h\,dh\,df$$

$$\times\int_0^{\frac{\pi}{2}}\sec^3\theta\left\{\cos\left[K_0(h'-h)\sec\theta\right]\right\}e^{-K_0(f+f')\sec^2\theta}\,d\theta$$

or

$$M_5' = M_{51}' + M_{52}' + M_{53}'$$

where

$$M_{51}' = -\frac{16\rho b^2 c^2}{\pi K_0^5 l^4}\int_0^{\frac{\pi}{2}}\left[1-e^{-K_0 d\sec^2\theta}\right]^2\Big\{2\left(K_0^2 l^2\cos^5\theta+\cos^7\theta\right)$$

$$+\text{ Real part of }\ 2\left[\cos^7\theta\,\left(K_0 l\sec\theta+i\right)^2 e^{2iK_0 l\sec\theta}\right]\Big\}\,d\theta$$

$$M_{52}' = \frac{16\rho b^2 c^2 e}{\pi K_0^4 l^4}\int_0^{\frac{\pi}{2}}\left[1-e^{-K_0 d\sec^2\theta}\right]^2\Big\{2\left(K_0^2 l^2\cos^3\theta+\cos^5\theta\right)$$

$$+\text{ Real part of }\ 2\left[\cos^5\theta\,\left(K_0 l\sec\theta+i\right)^2 e^{2iK_0 l\sec\theta}\right]\Big\}\,d\theta$$

$$M_{53}' = \frac{16\rho b^2 c^2 d}{\pi K_0^4 l^4}\int_0^{\frac{\pi}{2}}\left[1-e^{-K_0 d\sec^2\theta}\right]e^{-K_0 d\sec^2\theta}\Big\{2\left(K_0^2 l^2\cos^3\theta+\cos^5\theta\right)$$

$$+\text{ Real part of }\ 2\left[\cos^5\theta\,\left(K_0 l\sec\theta+i\right)^2 e^{2iK_0 l\sec\theta}\right]\Big\}\,d\theta$$

$$M_6'' = -\frac{32\rho K_0^2 b^2 c^2}{\pi l^4}\int_0^d\int_{-l}^{l}\left(f'-e\right)h'\,dh'\,df'\int_0^d\int_{L-l}^{L+l}\left(h-L\right)dh\,df$$

$$\times\int_0^{\frac{\pi}{2}}\sec^3\theta\left\{\cos\left[K_0\left(h'-h\right)\sec\theta\right]\right\}e^{-K_0\left(f+f'\right)\sec^2\theta}\,d\theta$$

or

$$M_6'' = M_{61}'' + M_{62}'' + M_{63}''$$

where

$$M_{61}'' = -\frac{32\rho b^2 c^2}{\pi K_0^5 l^4} \int_0^{\frac{\pi}{2}} \left[1 - e^{-K_0 d \sec^2\theta}\right]^2 \Big\{ 2\left(K_0^2 l^2 \cos^5\theta + \cos^7\theta\right) \cos\left(K_0 L \sec\theta\right)$$

$$+ \text{Real part of } \left[\cos^7\theta \left(K_0 l \sec\theta + i\right)^2 e^{-iK_0 L_1 \sec\theta}\right]$$

$$+ \text{Real part of } \left[\cos^7\theta \left(K_0 l \sec\theta + i\right)^2 e^{iK_0 L_2 \sec\theta}\right] \Big\} d\theta$$

$$M_{62}'' = \frac{32\rho b^2 c^2 6}{\pi K_0^4 l^4} \int_0^{\frac{\pi}{2}} \left[1 - e^{-K_0 d \sec^2\theta}\right]^2 \Big\{ 2\left(K_0^2 l^2 \cos^3\theta + \cos^5\theta\right) \cos\left(K_0 L \sec\theta\right)$$

$$+ \text{Real part of } \left[\cos^5\theta \left(K_0 l \sec\theta + i\right)^2 e^{-iK_0 L_1 \sec\theta}\right]$$

$$+ \text{Real part of } \left[\cos^5\theta \left(K_0 l \sec\theta + i\right)^2 e^{-iK_0 L_2 \sec\theta}\right] \Big\} d\theta$$

$$M_{63}'' = \frac{32\rho b^2 c^2 d}{\pi K_0^4 l^4} \int_0^{\frac{\pi}{2}} \left[1 - e^{-K_0 d \sec^2\theta}\right] e^{-K_0 d \sec\theta} \Big\{ 2\left(K_0^2 l^2 \cos^3\theta + \cos^5\theta\right) \cos\left(K_0 L \sec\theta\right)$$

$$+ \text{Real part of } \left[\cos^5\theta \left(K_0 l \sec\theta + i\right)^2 e^{-iK_0 L_1 \sec\theta}\right]$$

$$+ \text{Real part of } \left[\cos^5\theta \left(K_0 l \sec\theta + i\right)^2 e^{-iK_0 L_2 \sec\theta}\right] \Big\} d\theta$$

$$M_{10}''' = \frac{32\rho K_0^2 b^2 c^2}{\pi l^4} \int_0^d \int_{-l}^{l} (h')^2 dh' df' \int_0^d \int_{h'}^{l} h\, dh\, df$$

$$\times \int_0^{\frac{\pi}{2}} \sec^4\theta \left\{ \sin\left[K_0(h'-h)\sec\theta\right] \right\} e^{-K_0(f+f')\sec^2\theta} d\theta$$

$$M_{11}'' = \frac{32\rho K_0^2 b^2 c^2}{\pi l^4} \int_0^d \int_{-l}^{l} (h')^2 dh' df' \int_0^d \int_{L-l}^{L+l} (h-L)\, dh\, df$$

$$\times \int_0^{\frac{\pi}{2}} \sec^4\theta \left\{ \sin\left[K_0(h'-h)\sec\theta\right] \right\} e^{-K_0(f+f')\sec^2\theta} d\theta$$

The components Z_4''', M_5'', M_{10}''' represent force and moments acting on the trailing ship as if it were alone, and components X_6'', Z_5'', M_6'' and M_{11}'' are due to wave interference. In terms of the system of sources and sinks used to replace the two ships, the interpretation of the foregoing force and moment components is as follows:

X_6'' is one part of the resultant horizontal force acting on the trailing ship (distribution A), and the trailing system of sources and sinks behind the leading ship (distribution B).

Z_4''' is one part of the resultant vertical force on the distribution A due to the forces between the distribution A and the trailing system of sources and sinks behind the distribution A.

Z_5'' is one part of the resultant vertical force on the distribution A due to the forces between the trailing system of sources and sinks behind the distribution B and the distribution A itself.

M_5' is one part of the resultant moment on the distribution A due to the horizontal components of the forces between the distribution A and the trailing system of sources and sinks behind the distribution A.

M_6'' is one part of the resultant moment on the distribution A due to the horizontal components of the forces between the distribution A and the trailing system of sources and sinks behind the distribution B.

M_{10}''' is one part of the resultant moment on the distribution A due to the vertical components of the forces between the distribution A and the trailing system of sources and sinks behind the distribution A.

M_{11}'' is one part of the resultant moment on the distribution A due to the vertical components of the forces between the distribution A and the trailing system of sources and sinks behind the distribution B.

Figures 1 through 7 show the variation of the effect of wave interference with respect to the spacing between ships. The forces and moments acting on the trailing ship as if it were alone do not vary with the distance between ships. The parameters used in the calculations are: (1) the ratio of the distance between ship centers and ship length, $\alpha = L/2l$, and the corresponding quantities $\alpha' = L_1/2l = \alpha - 1$ and $\alpha'' = L_2/2l = \alpha + 2$; (2) draft ship length ratio, $\beta = d/2l$; (3) ratio of the distance from the origin of the axes to the center of mass of the ship and the ship length, $\epsilon/2l$; and (4) the inverse of the square root of Froude's number, $p = 1/\sqrt{F}$. The values chosen for these various parameters are as follows:

$\alpha = 2$ through 7

$\beta = 0.1$

$\epsilon/2l = 1/40$

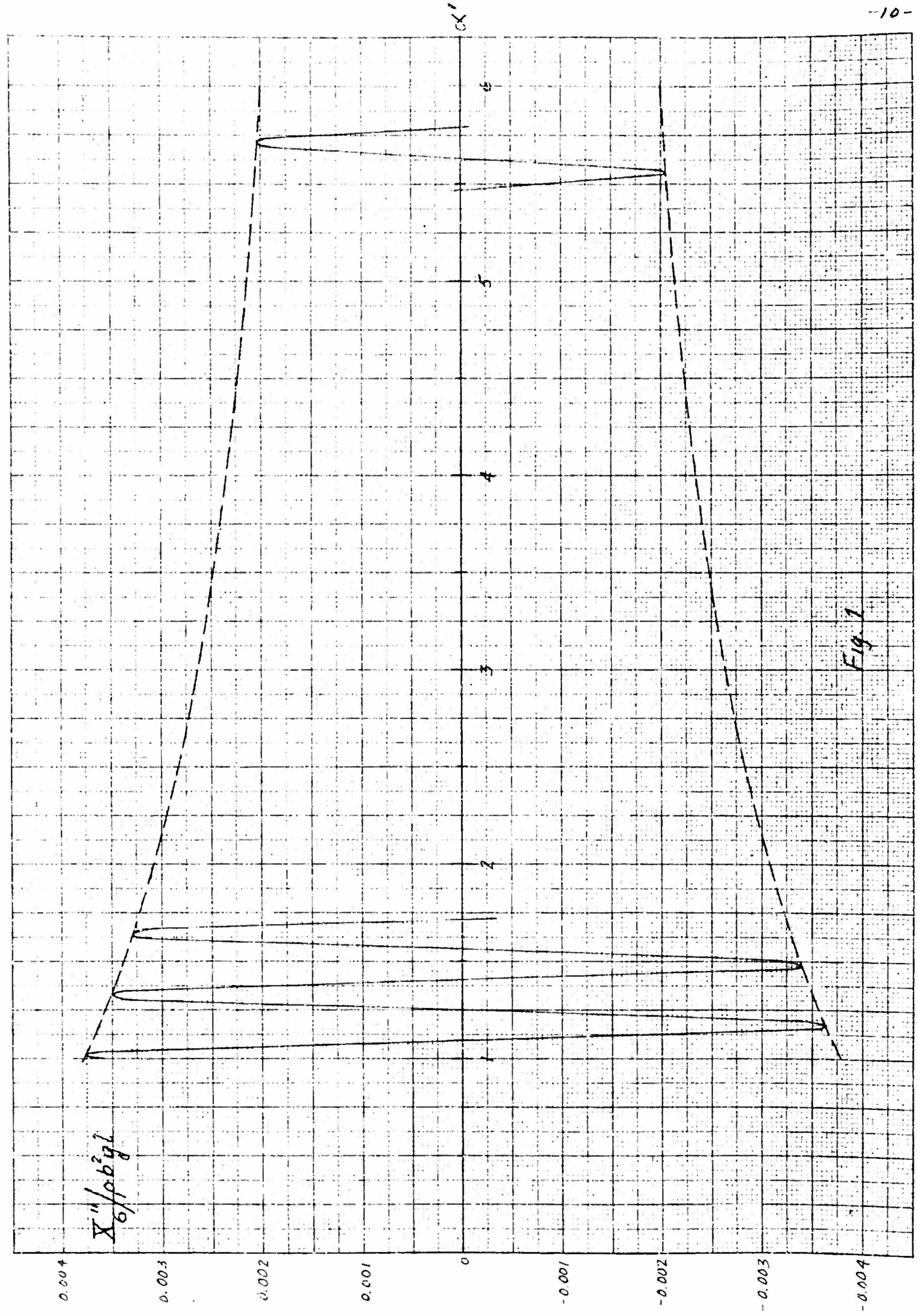
$p = 20$

The following remarks will be confined only to the effect of wave interference on the trailing ship.

The curves representing the effect of the leading ship on the trailing ship are all of an oscillatory nature. They are damped very slowly and the frequency with which they vary remains practically constant with increasing distance between ships. It is surprising that even for a relatively large distance of six ship lengths, where one would expect negligible effect, there is an appreciable value for the separate components. This may be due to the fact that the problem is idealized to include various assumptions which render it amenable to mathematical analysis; the most drastic deviation from actuality probably is the use of a non-viscous fluid. Despite the assumptions used, the analysis and calculations give a qualitative description of the phenomenon as was evidenced by experiments conducted by Barrillon, a French naval architect, in 1926. He detected that the effect of the leading ship on the trailing ship oscillated and diminished very slowly with distance. Even at a spacing of five or six ship lengths the effect was measurable.

At the speed chosen in the calculations, all the curves oscillate at the rate of about three cycles per ship length. The equations for the various forces and moments indicate that as the speed increases the frequency per ship length decreases. Thus, the effect of the leading ship on the trailing ship is more sensitive to the spacing between ships at low speeds than at high speeds. At low speeds then, a small change in the spacing between is likely to change the wave effect from a maximum reduction to a maximum increase. However, the trailing ship would probably not experience any oscillating motion if the distance between the ships is continuously increasing or decreasing. The total wave effect of the leading ship on the trailing ship would not amount to more than five per cent of the total forces and moments due to all causes acting on the trailing ship. This small oscillating force acting on the large mass of the ship would not be sufficient to cause any appreciable surge, pitch, or heaving.

The writing of a comprehensive and concluding report on the additional wave forces and moment experienced by a trailing ship is planned for the month of June.


$X''_6/\rho b^2 g l$
α'
1
2
3
4
5
6
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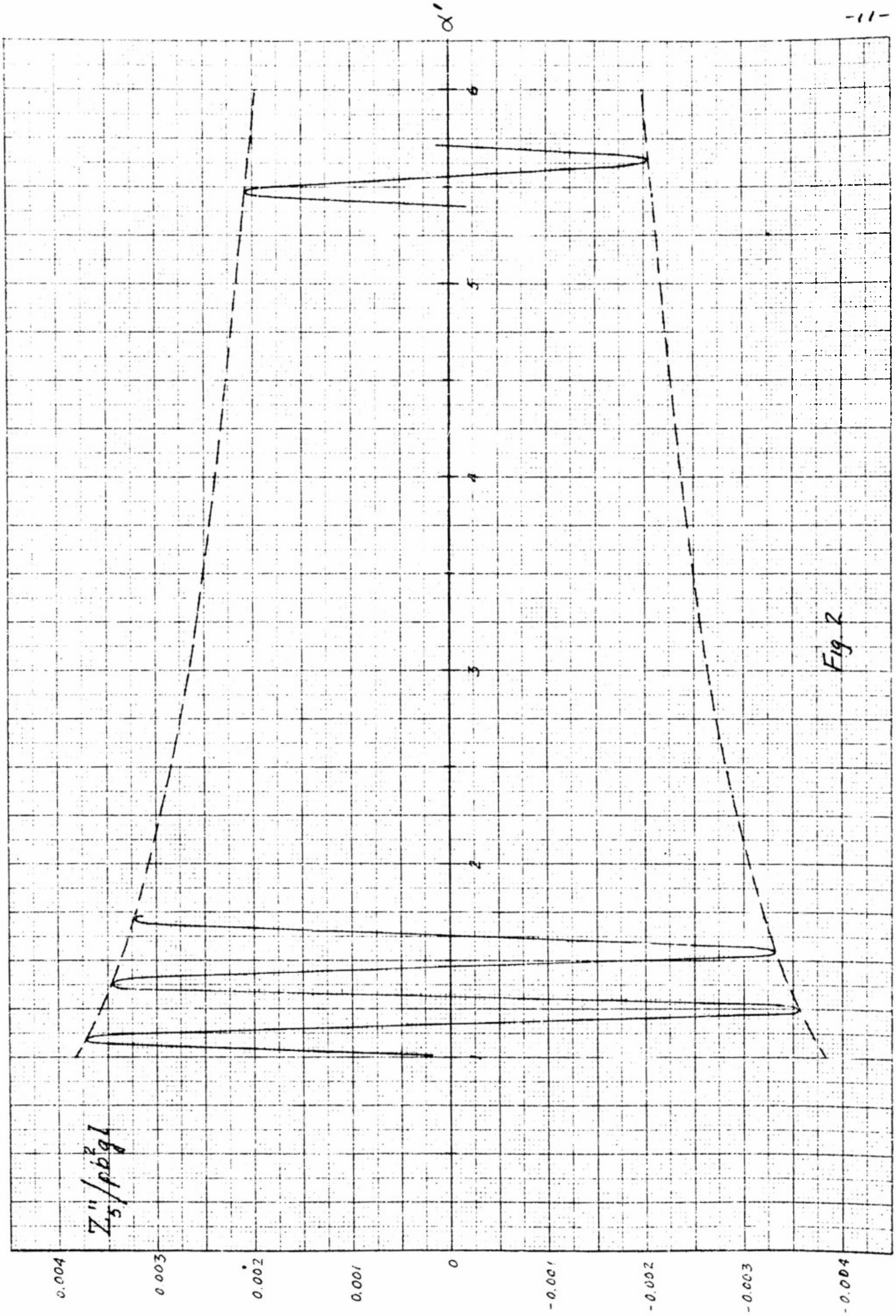
0.003
0.002
0.001
0
-0.001
-0.002
-0.003
-0.004

Fig. 1



α'
1
2
3
4
5
6
$Z_5''/\rho b^2 g l$
0.004
0.003
0.002
0.001
0
-0.001
-0.002
-0.003
-0.004

Fig 2

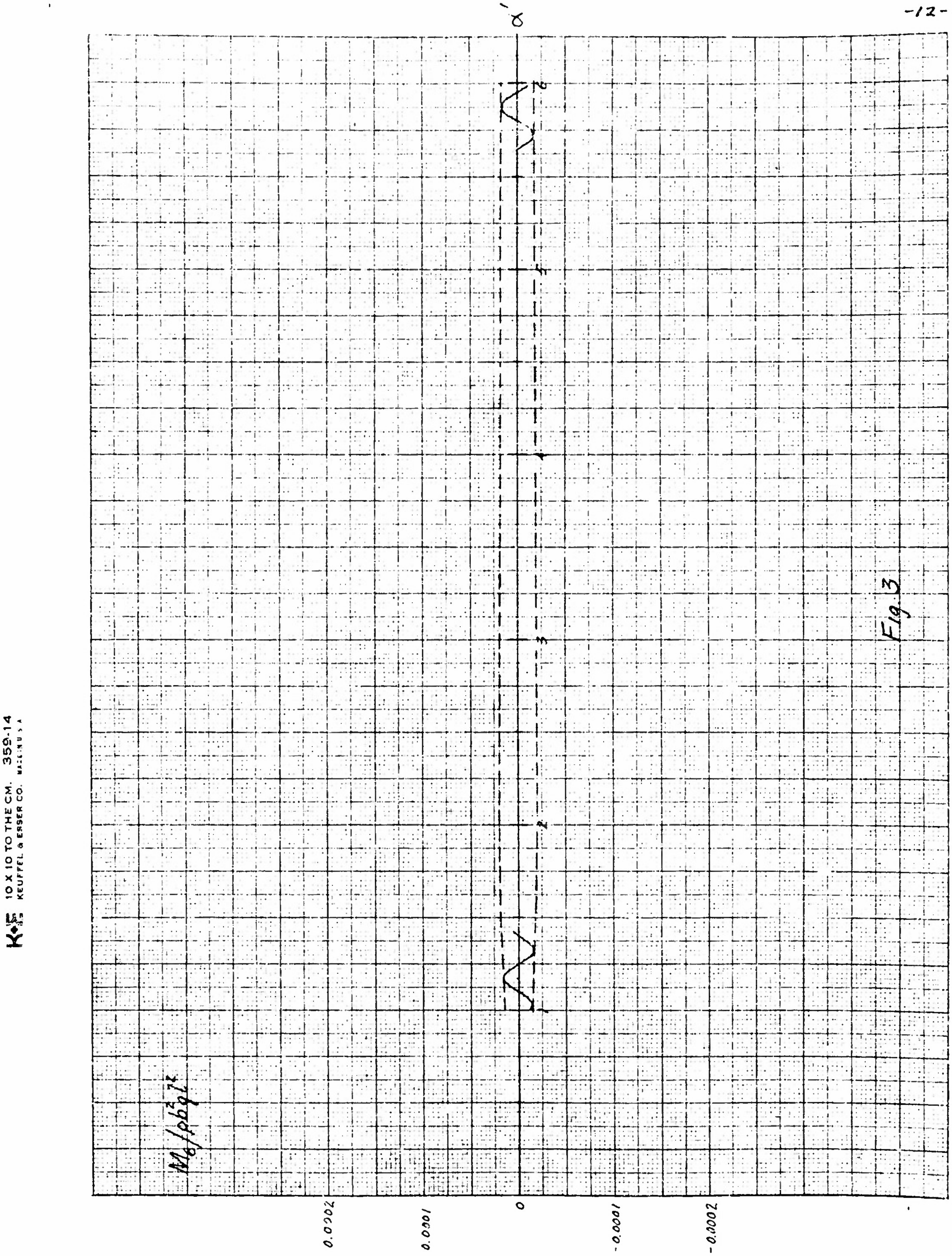

α'
0.0002
0.0001
0
-0.0001
-0.0002
1
2
3
4
5
2
$M_\delta/\rho b q^2 \tau^2$
K+E 10 X 10 TO THE CM. 359-14
KEUFFEL & ESSER CO.

Fig.3

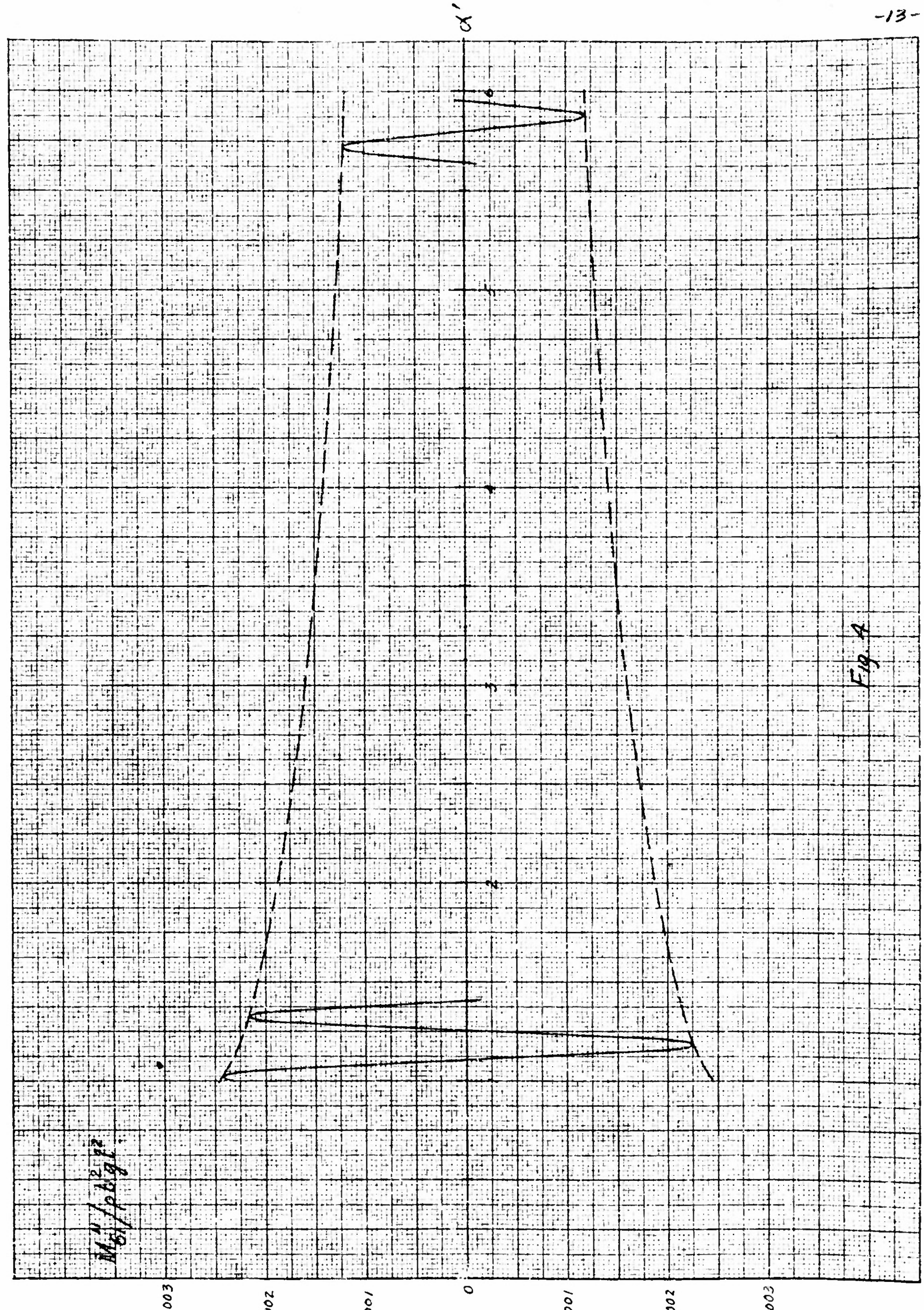
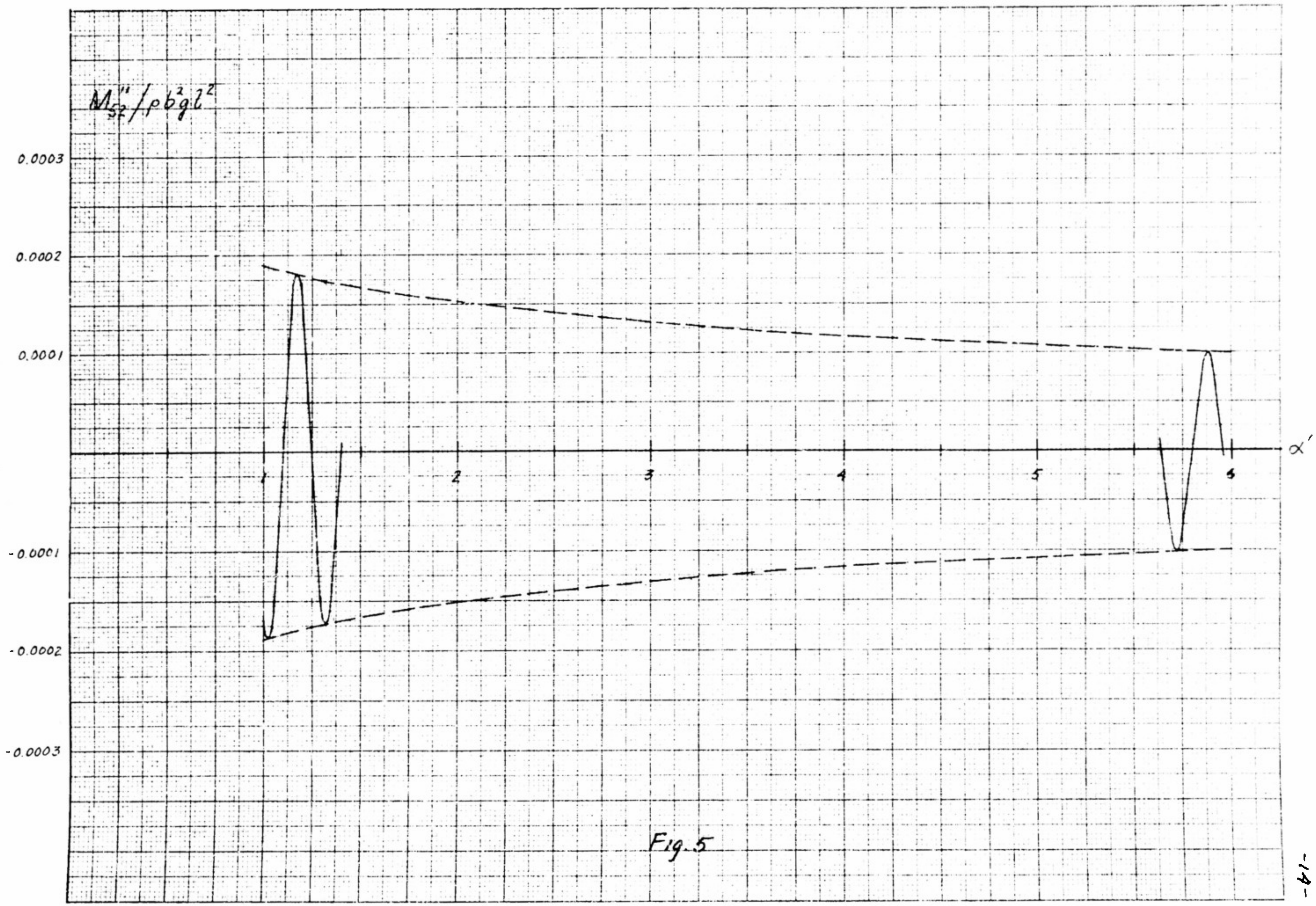


Fig. 4


$M''_{52}/\rho b^2 g l^2$
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0.0002
0.0001
-0.0001
-0.0002
-0.0003
1
2
3
4
5
6
α'

Fig. 5

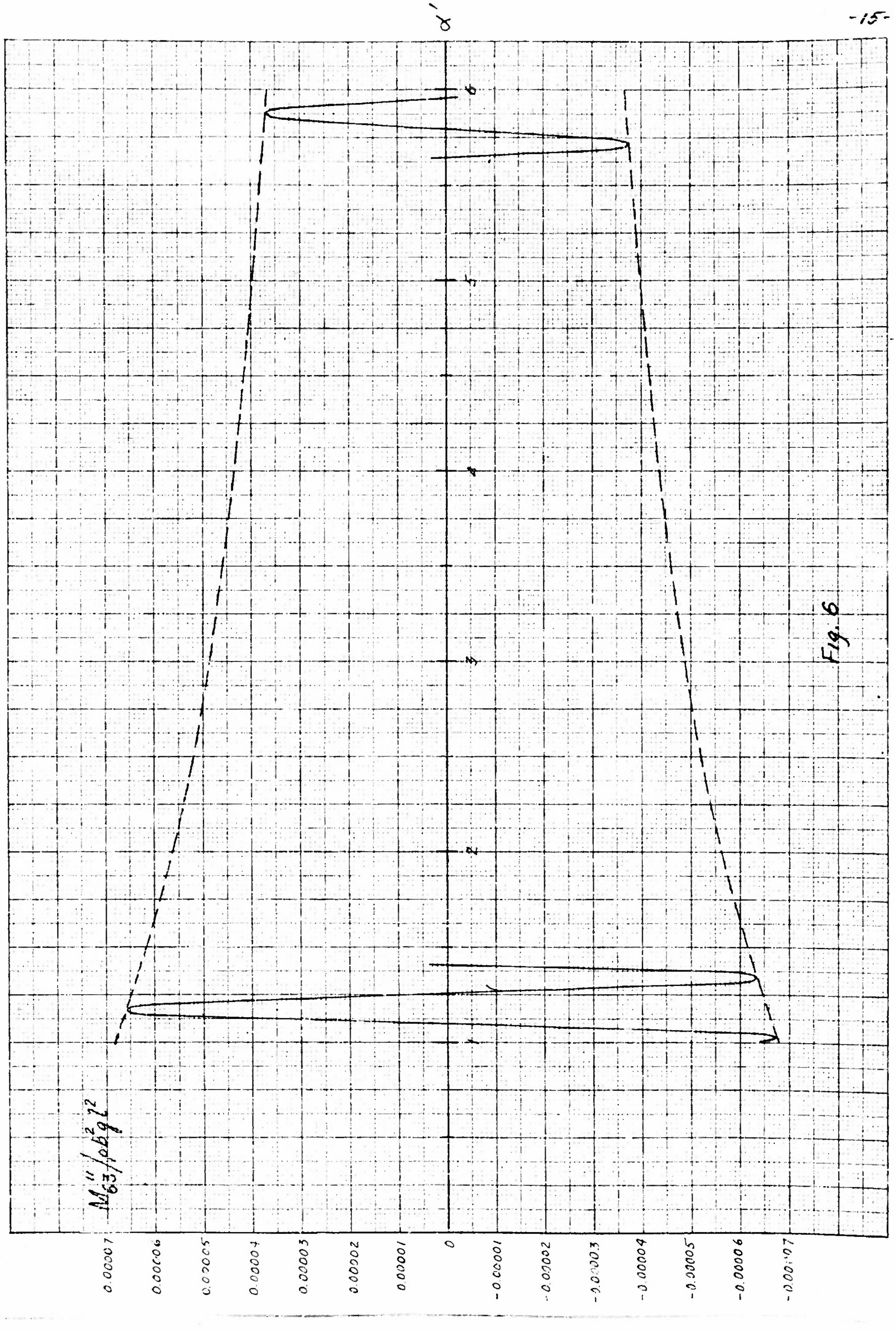
α'
1
2
3
4
5
6
$M''_{63}/\rho b^2 g l^2$
0.00007
0.00006
0.00005
0.00004
0.00003
0.00002
0.00001
0
-0.00001
-0.00002
-0.00003
-0.00004
-0.00005
-0.00006
-0.00007

Fig. 6

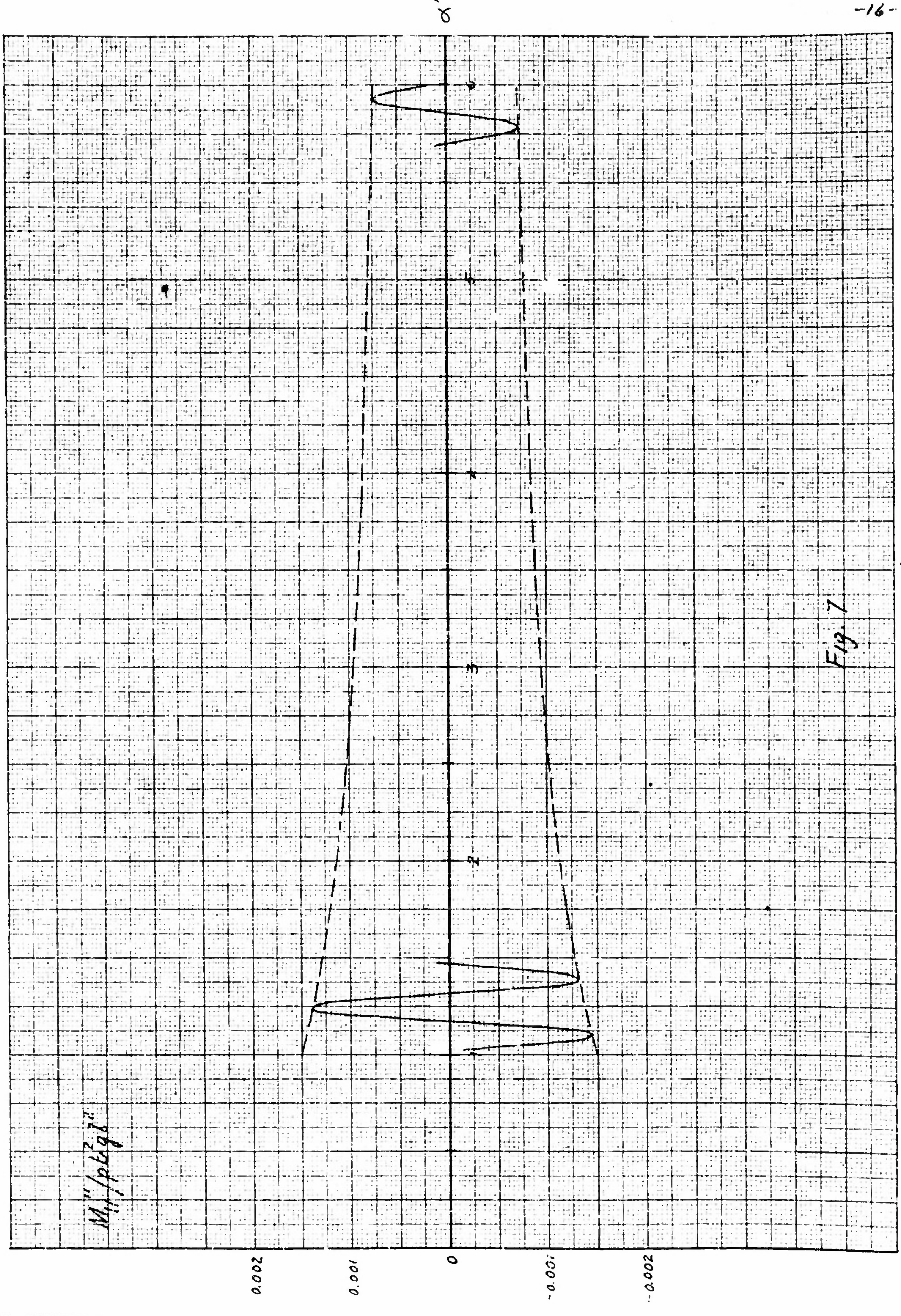

Fig. 7

Part II Hydrofoils

A preliminary investigation of the problem of oscillation of bodies under a free surface of an incompressible fluid has been underway for the last eight weeks. The goal of this preliminary investigation is to review critically the existing literature in this field for the following purposes: (1) to note the methods of analysis, (2) to review the assumptions in the analysis, (3) to interpret the results of analysis, and (4) to ascertain whether portions of previous analysis would be applicable to our problem on steady oscillation of flat foils moving with a constant velocity below a free surface.

The available Russian reports by Kotchin were the first to be reviewed carefully. In many respects these reports reveal a method of analysis that is both general and applicable to a wide class of hydrodynamic problems. However, the restriction and assumptions that are introduced in his development appear to be questionable. For example, the mean values of certain time-dependent integrals were assumed to be zero. Moreover Kotchin's analysis does not take into account the vortex trail arising from the oscillation of the foil. Thus these ommissions imply a lift force that is only partially correct. These ommissions and their limitations on the magnitude of the lift force were not discussed by Kotchin. They may be small in some instances, and further investigations are needed. Finally, several mathematical steps in his study are questionable, or if restrictions are implied, they were not stated. However, the procedure employed by Kotchin together with suitable corrections might prove a potential method of analysis.

Kuessner's more recent report on the problem of unsteady lifting surface is an excellent source of information of various methods employed by the aeronautical scientists for the past thirty years. Kuessner was able to formulate and to solve the boundary value problem with a minimum of physical facts and he was also able to obtain valuable generalizations. The transformation of coordinates together with a certain amount of additional information found in Juessner's paper appears to be useful for the study of the problem of unsteady lifting surfaces placed below a free-surface. Sear's report in this same area, although of earlier date, emphasizes the physical interpretation of the role placed by the trailing vortex sheet. He was able to show the separation of total lift into three parts and the significance of each part.

Our plan for the remaining month of May and the early part of June is to review several other papers. After this is done, the solution of the proposed problem will be started. It is believed that parts of the above background material eventually will be of valuable assistance in carrying out either the method or procedure of solving our problem.